

Tunneling between Dilute GaAs Hole Layers

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We report interlayer tunneling measurements between very dilute two-dimensional GaAs hole layers. Surprisingly, the shape and temperature-dependence of the tunneling spectrum can be explained with a Fermi liquid-based tunneling model, but the peak amplitude is much larger than expected from the available hole band parameters. Data as a function of parallel magnetic field reveal additional anomalous features, including a recurrence of a zero-bias tunneling peak at very large fields. In a perpendicular magnetic field, we observe a robust and narrow tunneling peak at total filling factor $\nu_T = 1$, signaling the formation of a bilayer quantum Hall ferromagnet.

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Measurements of tunneling between a pair of low-disorder, GaAs two-dimensional electron systems (2DESs) have revealed some of the most basic [1, 2, 3, 4, 5, 6], as well as exotic [7] properties of these systems. The measurements have probed, e.g., the Fermi contour of the 2D electrons [1], and have determined their quantum lifetime [3, 4, 5, 6, 8, 9, 10, 11, 12]. More recently, tunneling experiments on closely spaced, interacting electron bilayers at the total Landau level filling factor $\nu_T = 1$ revealed an unusual, excitonic quantum Hall ground state [7].

Here we report an experimental study of the differential tunneling conductance between very dilute, closely spaced GaAs 2D *hole* systems (2DHS) as a function of interlayer bias [13]. In each of the layers, the inter-hole distance measured in units of the effective Bohr radius, $r_s = \frac{m^* e^2}{4\pi\epsilon\epsilon_0\hbar^2\sqrt{\pi p}}$, reaches up to $\simeq 13$, attesting to the extreme diluteness of the 2DHS (here, p is the 2D hole density in each layer, $m^* = 0.2m_0$ is the hole effective mass [14], and $\epsilon = 12.4$ is the GaAs dielectric constant). The physics of such a dilute system is expected to be dominated by interaction effects. Indeed, in the presence of a perpendicular magnetic field (B_\perp) and at total Landau level filling factor $\nu_T = 1$, we observe a strong zero-bias tunneling peak which persists up to a temperature of $T \simeq 0.6\text{K}$, indicative of significant interlayer *and* intralayer interaction in this system [7]. Despite the extreme diluteness of our bilayer 2DHS, the shape and temperature-dependence of the tunneling peak in *zero* applied magnetic field are consistent with an existing model based on Fermi liquid theory [8, 9]. The peak amplitude, however, is roughly 8 orders of magnitude larger than that calculated using the conventional hole band parameters. Our measurements in samples with different barrier thicknesses suggest that the hole mass relevant to tunneling through an AlAs barrier is much smaller than expected. Finally, tunneling measurements performed with an applied parallel magnetic field B_\parallel reveal another puzzle: while the amplitude of the zero-bias tunneling peak quickly decays with B_\parallel consistent with the expected momentum conservation requirement, the peak reappears at very large B_\parallel .

We performed interlayer tunneling measurements on double quantum well samples grown on GaAs (311)A substrates. The structures consist of a pair of 15 nm-wide GaAs quantum wells, separated by 7.5, 8.0, or 11 nm AlAs barriers, and flanked by Si-modulation-doped layers of $\text{Al}_{0.21}\text{Ga}_{0.79}\text{As}$. While we will discuss the data from all three samples, the data shown in this report are all from the sample with a 7.5 nm barrier. The as-grown density for this sample is $\simeq 2 \times 10^{10}$ per layer, and the typical mobility at 0.3 K is $\simeq 20 \text{ m}^2/\text{Vs}$. A Y-shaped mesa, illustrated schematically in the inset to Fig. 1(a), with an active region of $100 \mu\text{m} \times 700 \mu\text{m}$, was etched into the wafer. Alloyed InZn contacts at the ends of the seven arms allow for making independent contacts to individual 2D hole layers using the selective gate depletion scheme [15]. This Y-configuration enables us to measure electrical transport in each of the two layers separately, and to balance their densities using front and back gates which cover the active area, before proceeding with the interlayer tunneling measurements. The latter were performed by applying a low-frequency, $18\mu\text{V}$ peak-to-peak *ac* excitation on top of an interlayer *dc* bias to the top layer, and measuring the current in the back layer using standard lock-in techniques. The lock-in phase was set by confirming that the measured differential (*ac*) conductance matched the derivative of the *dc* $I - V$ curve for the tunneling measurement.

As illustrated in Fig. 1(a), the differential conductance of the tunnel junction formed by the pair of 2D hole sheets with equal carrier density shows a pronounced resonance near zero interlayer bias. This zero-bias resonance is remarkably similar to that seen previously in bilayer *electron* samples [2, 3, 4, 5, 6], despite here being taken in the extremely dilute limit ($r_s \simeq 11 - 13$ for holes, $r_s \simeq 1 - 6$ for electrons). In the earlier works [4, 5, 6], the *dc* conductance, I/V , derived from the data was found to closely match a theoretically derived [8, 9] expression: $\frac{I}{V}(V) = St^2 \frac{2e}{\hbar} \frac{m^*}{\pi\hbar^2} \frac{\Gamma}{(eV)^2 + \Gamma^2}$, where S is the area of the tunnel junction, t is the tunneling matrix element, m^* is the density-of-states effective mass for the 2D carriers, Γ is inversely proportional to the quasiparticle scattering

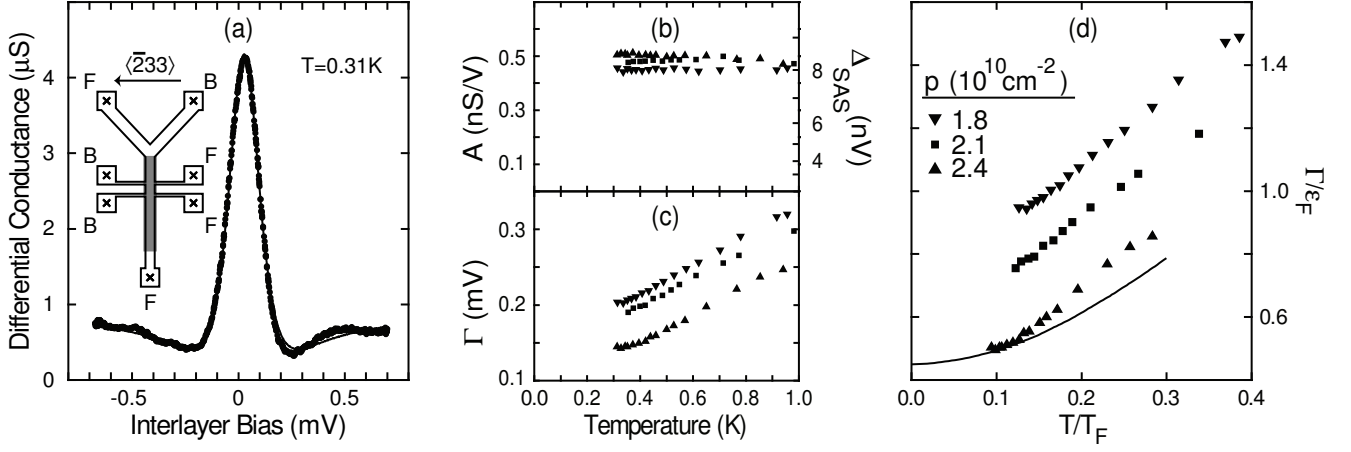


FIG. 1: (a) The differential conductance of the bilayer hole system as a function of interlayer bias. The layers have equal densities of $p = 2.4 \times 10^{10} \text{ cm}^{-2}$, corresponding to an r_s of 11, and are separated by a 7.5 nm thick AlAs barrier. The solid line represents a fit of Eq. (1) to the data. The inset shows a schematic diagram of our Hall bar. Front and back gates cover the active (gray) area to allow for tuning the density of each layer. Contacts (crosses) can be made to either the front (F) or back (B) layer by energizing selective, depletion (contact) gates (not shown) on the back or front of the sample, respectively. Tunneling measurements were performed by energizing all the contact gates, and using only the four contacts in the middle of the Hall bar. (b & c) Tunneling amplitude (A) and width (Γ), derived from fitting the data to Eq. (1), are shown as a function of temperature for three layer densities: $p = 1.8 \times 10^{10} \text{ cm}^{-2}$ ($r_s = 13$), $2.1 \times 10^{10} \text{ cm}^{-2}$ ($r_s = 12$), and $2.4 \times 10^{10} \text{ cm}^{-2}$ ($r_s = 11$). Definition of symbols is provided in the inset to (d). (d) The width Γ , scaled to the Fermi energy (ϵ_F), is shown as a function of the temperature T , scaled to the Fermi temperature (T_F). The solid line is the theoretical prediction from Fig. 8 of Ref. 9, offset vertically to account for the disorder scattering in our sample at $p = 2.4 \times 10^{10} \text{ cm}^{-2}$.

lifetime, and both Γ and $|eV|$ are assumed to be much smaller than the Fermi energy E_F . This zero-bias resonance results from a close matching of the momenta and energies of the carriers in the two wells. In Fig. 1(a), we show a fit of our data to the differential conductance derived from this expression [16],

$$\frac{dI}{dV}(V) = A\Gamma \frac{\Gamma^2 - (eV)^2}{[\Gamma^2 + (eV)^2]^2} \quad (1)$$

where $A = St^2 \frac{2e}{h} \frac{m^*}{\pi \hbar^2}$. As seen in Fig. 1(a), this expression provides a remarkably good fit to the experimental data, despite a Γ (0.15 mV at 0.31 K) and applied bias which are comparable to the Fermi energy (0.29 mV).

In Fig. 1(b & c) we summarize the T -dependence of values of A and Γ extracted from the fits of our data to Eq. (1). In general, the width Γ is inversely proportional to the quasiparticle scattering lifetime. As seen in Fig. 1(c), the fitted widths for all three carrier concentrations appear to extrapolate to finite values as $T \rightarrow 0$. Static disorder, mainly from ionized impurities, is believed to lead to a finite zero- T scattering lifetime, and hence a finite tunneling peak width [4, 5]. Our observed decrease in the extrapolated zero- T width with increasing carrier concentration is likely a result of the improved screening of the disorder, and is consistent with previous bilayer electron data. The increase of Γ with increasing T in the bilayer electron case has been attributed to carrier-carrier scattering [3, 4, 5]. Jungwirth and MacDonald [9] calculated this scattering, and found excellent, quan-

titative agreement with the electron bilayer data [4]. As shown in Fig. 1(d), this prediction underestimates the change in the measured width as a function of temperature for our data. The discrepancy is possibly due to the very large r_s in our system [9].

In Fig. 1(b) we observe that the amplitude A is T independent to within $\pm 2.5\%$ for the three densities investigated here. According to Eq. (1), the amplitude A is proportional to the square of the tunneling matrix element t , which is intuitively T independent. In a single-particle picture, t is the hopping matrix element between the two planes, and is related to the energy splitting between symmetric and antisymmetric wavefunctions spanning the two wells, $2t = \Delta_{SAS}$. Using a density-of-states effective mass $m^* = 0.2m_0$ [14], we find $\Delta_{SAS} = 8.6$ nV for $p = 2.4 \times 10^{10} \text{ cm}^{-2}$ and slightly smaller for lower p (see Fig. 1(b)). These Δ_{SAS} values are 4 orders of magnitude larger than expected from simple estimates of Δ_{SAS} based on the structure of our bilayer system and the hole band parameters [17].

Are strong interlayer correlations responsible for the anomalously large zero-bias tunneling peak that we observe in our very dilute bilayer sample? Note that in our sample the ratio of the average in-plane interparticle distance $\langle r \rangle = 1/\sqrt{p}$ to the interlayer distance d is about 2.9-3.3 (we define d as the center-to-center distance between the two quantum wells). If the large tunneling peak is indeed related to the diluteness of our bilayer layer system, then we would expect a similarly large peak

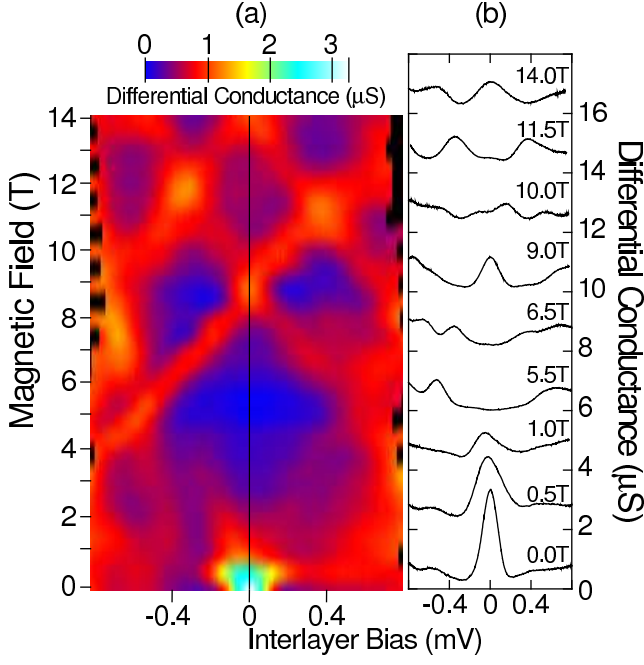


FIG. 2: (a) (Color online) False color plot of the differential tunnel conductance of the hole bilayer as a function of interlayer bias and applied parallel magnetic field. Data were taken at 0.31K and a hole density of $2.1 \times 10^{10} \text{ cm}^{-2}$ per layer. For clarity, the tunneling traces shown in (b) have been offset vertically (in steps of $2 \mu\text{S}$).

in samples that have a similar $\langle r \rangle/d$ ratio but whose barrier is slightly thicker. Our measurements on two other samples with $\langle r \rangle/d \sim 3$, however, indicate otherwise: In a sample with a barrier width $w_B = 8.0 \text{ nm}$ we observe a tunneling peak whose amplitude is a factor of ~ 10 smaller than the peak for the 7.5 nm -barrier sample, and in a sample with $w_B = 11 \text{ nm}$ there is no measurable tunneling. These observations are, on the other hand, consistent with a single-particle picture in which Δ_{SAS} is exponentially sensitive to the width of the barrier [18]. To be quantitative, using a self-consistent Shroedinger solver for our sample structure, we find that the calculated values of Δ_{SAS} approach those extracted from the measured data for both 7.5 nm - and 8.0 nm -barrier samples if we take $m_z = 0.19m_0$ as the mass in the growth direction, instead of the expected value $m_z = 0.63m_0$ [17, 19]. While our assumption of a single mass for the growth direction means we cannot directly interpret this value as being the mass of holes in AlAs in the growth direction, our data do strongly suggest that the hole mass relevant to tunneling through an AlAs barrier is smaller than has been suggested in the literature [17].

The zero-bias tunneling peak arises from a close matching of both the energy and *momentum* of the carriers in the layers. By applying a magnetic field $B_{||}$ parallel to the layers, the in-plane (canonical) momenta of the carriers in one well shift with respect to the other by $k_d =$

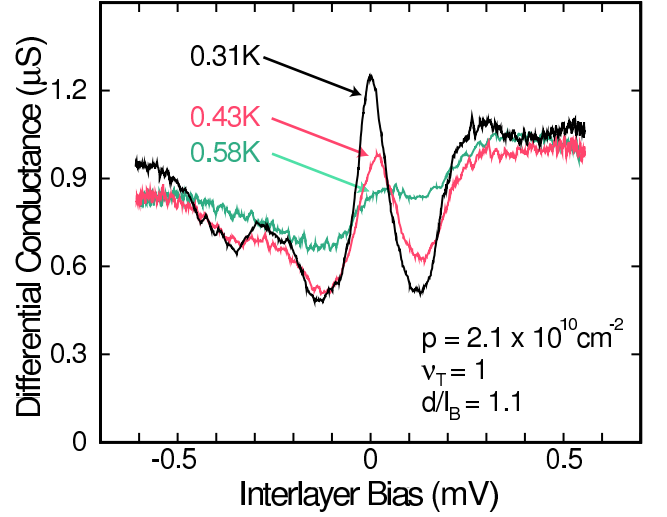


FIG. 3: (Color online) The differential tunnel conductance as a function of interlayer bias is shown at a layer density of $2.1 \times 10^{10} \text{ cm}^{-2}$ in a perpendicular field of $B_{\perp} = 1.72 \text{ T}$, corresponding to a total (bilayer) filling factor of $\nu_T = 1$.

$(eB_{||}d)/\hbar$ [20]. We would expect the zero-bias peak to have maximum amplitude at zero field, where the Fermi contours of the two layers overlap, and decrease rapidly as the carrier momenta in one layer are shifted with $B_{||}$ and no longer overlap the momenta in the other layer [1, 8]. As shown in Fig. 2, we find that there is indeed a rapid suppression of the zero-bias peak upon the application of a small $B_{||}$ [21], of the order of 1 T. However, Fig. 2 reveals a very rich and puzzling evolution of the tunneling spectra at higher $B_{||}$. If we assume parabolic in-plane dispersions, the zero-bias tunneling peak should disappear beyond $B_{||}^c = (2\hbar k_F)/(ed) = 2.1 \text{ T}$, where $k_F = \sqrt{2\pi p}$ is the Fermi wavevector assuming a spin-degenerate system [22]. However, well beyond this field, we find peaks which evolve smoothly as a function of bias and $B_{||}$, with two dispersing peaks intersecting near zero bias at $\simeq 9 \text{ T}$ and $\simeq 14 \text{ T}$. This suggests a strong distortion of the hole bands and Fermi contours in a large $B_{||}$. In particular, a simple change in the band structure curvature, due to the finite hole layer thickness [23], would not explain the re-emergence of a zero-bias peak at high $B_{||}$.

Finally we present tunneling data in our bilayer hole system in a perpendicular magnetic field, B_{\perp} . As has been shown in bilayer electron samples with strong interlayer interaction, when B_{\perp} is tuned such that the total Landau level filling factor (ν_T) is one, a many-body zero-bias tunneling resonance ensues [7]. With each layer at a filling factor of $1/2$, if the ratio of the in-plane to the out-of-plane Coulomb energy, parameterized by d/l_B (where l_B is the magnetic length) is ≤ 1.8 , the occupied states in one layer are spatially correlated with vacant states in the other layer, and tunneling is resonantly enhanced [7]. This pairing has been further confirmed in both elec-

tron and hole bilayers using counterflow transport studies [24, 25, 26, 27]. Here we provide tunneling data (Fig. 3) for this unique state for our bilayer 2DHS. Despite a higher background level than the zero-field tunneling data, there is a strong zero-bias tunneling peak, persisting up to $T \simeq 0.6$ K. This is higher than the temperatures where the equivalent peak in bilayer electron samples disappears [6, 28] and reflects the very strong pairing in our sample: the parameter $d/l_B = 1.1$ for our sample is indeed smaller than $d/l_B > 1.5$ for the published electron bilayer data. This persistence of the tunneling peak up to higher temperatures is also consistent with the counterflow measurements in bilayer hole samples with relatively small d/l_B values [25, 27]. We defer a detailed discussion of the $\nu_T = 1$ bilayer hole tunneling peak height and width on temperature and d/l_B to a future communication.

In conclusion, we have demonstrated that certain aspects of interlayer tunneling in dilute bilayer 2D hole systems are remarkably similar to what has been seen in bilayer electrons. The shape and width of the zero-field tunneling peak can be well explained in terms of a Fermi liquid theory developed to understand the electron data. The anomalously large size of the zero-field peak is consistent with a smaller than expected hole mass relevant to tunneling through an AlAs barrier. The parallel magnetic field dependence of the tunneling spectra reveals surprises when compared to what is qualitatively expected based on a simple band structure. Finally, data taken in perpendicular field show enhanced tunneling at $\nu_T = 1$ in bilayer holes at relatively high temperatures, consistent with the system being deep in the strongly-interacting regime.

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